

# The Warm-Hot Universe

## An Introduction

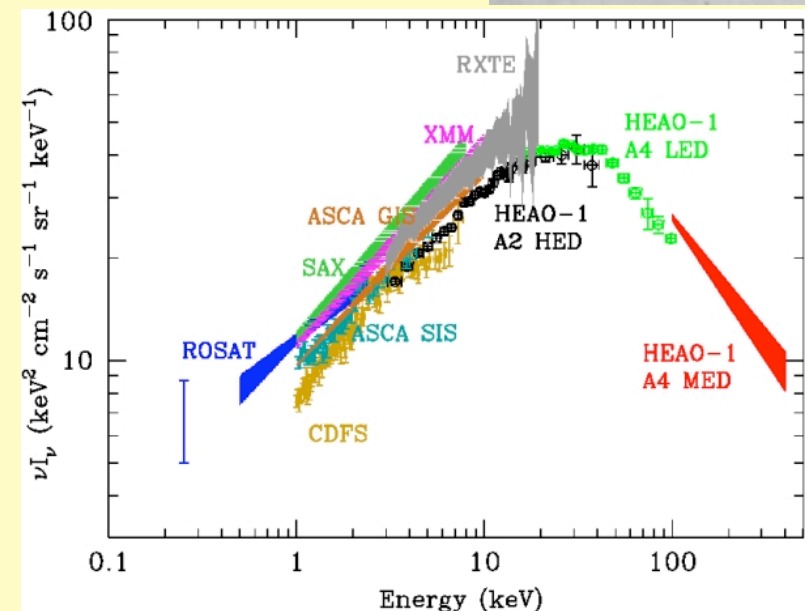
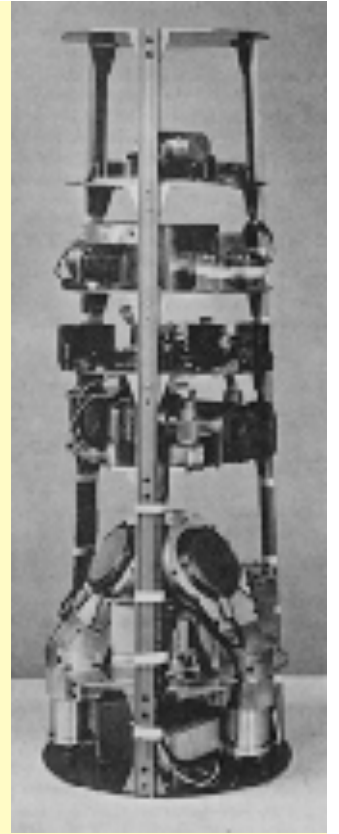
Roger Blandford  
KIPAC  
Stanford

# X-Ray Background

- Giacconi et al 1962
- Aerobee sounding rocket
  - cf Ariel 1
- Detect XRB
  - 40 keV IGM!
  - Now  $\sim 3 \times 10^8$  AGN

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# X-ray Clusters

- Optical clusters
  - Zwicky, Abell (4000)
- X-rays
  - Uhuru 1970s
- ROSAT BCS
  - 300 clusters



# Groups and Galaxies

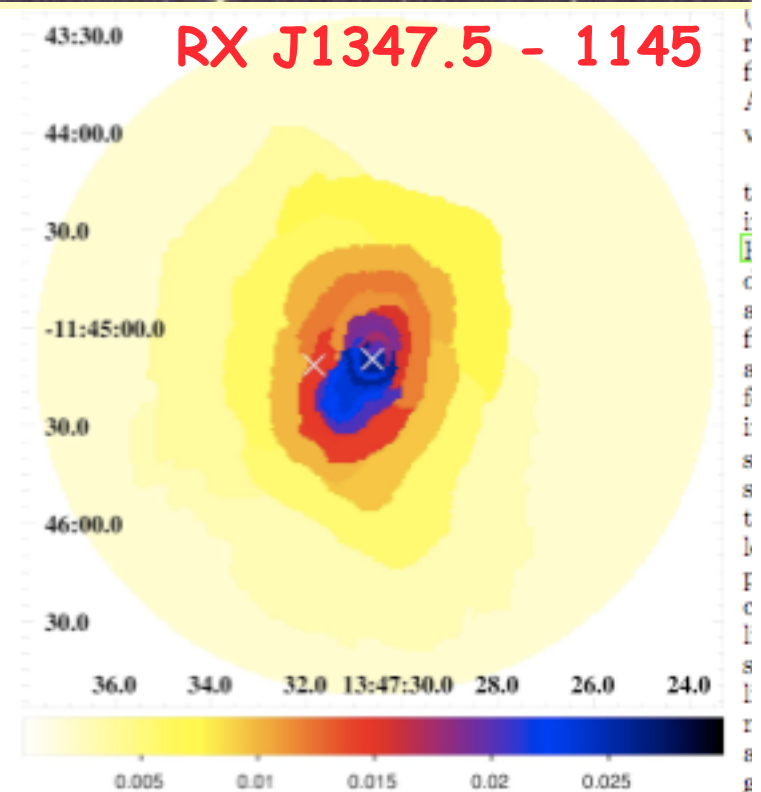
- Galaxies retain hot halos especially when massive
  - FUSE Galaxy observations ( $1-3 \times 10^5 \text{K}$ )
- Retain gas despite tidal and ram pressure stripping especially when massive ellipticals

Can we use to trace interaction history?

# Non X-ray Observations

- Much improved agreement between X-ray and weak + strong lensing mass distributions
- Gas distribution also consistent
- Consistency with SZ?
- Thermal energy not  $n^2$

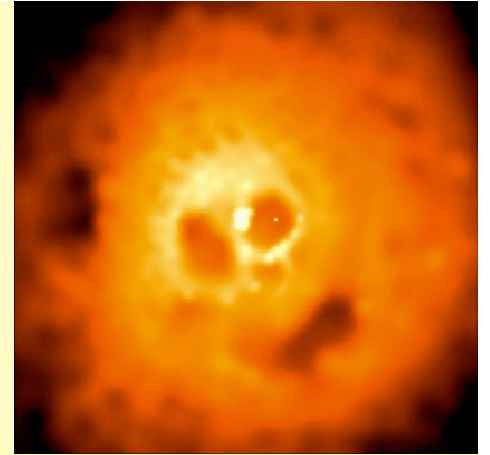
Is this now typical?



# Scaling relations

- eg  $M \sim T^{1.5}$ ,  $L(T)$  relation
- Definition of  $M$ ,  $L$ 
  - Does not converge!
  - Need consistent profile definitions etc
- Consistency with simulations?
  - Validation of cluster counting proposals

# (Non) Cooling (Non)Flows



- $1000 M_{\text{sun}} \text{ yr}^{-1}?!$ 
  - Gas cools to  $\sim 0.3 \text{ T}$  then vanishes independent of starting temperature?
- Is it heated and maintained at this temperature by radio bubbles??
  - Sound waves, internal waves, wakes,
- Does it radiate in some other band?
  - eg far ultraviolet
- Is cosmic ray pressure important

# Excess emission

- Soft Excess
- Hard Excess
- Very difficult observations
  - Background subtraction
  - Instrumental effects
  - Absorption
- Additional thermal components?
  - bremsstrahlung
- Cosmic ray electrons
  - Radio halos eg Coma C
  - Synchrotron or inverse Compton?

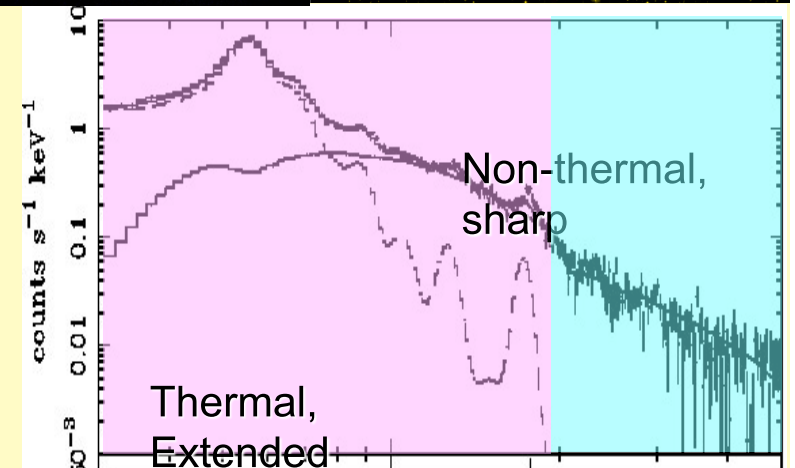
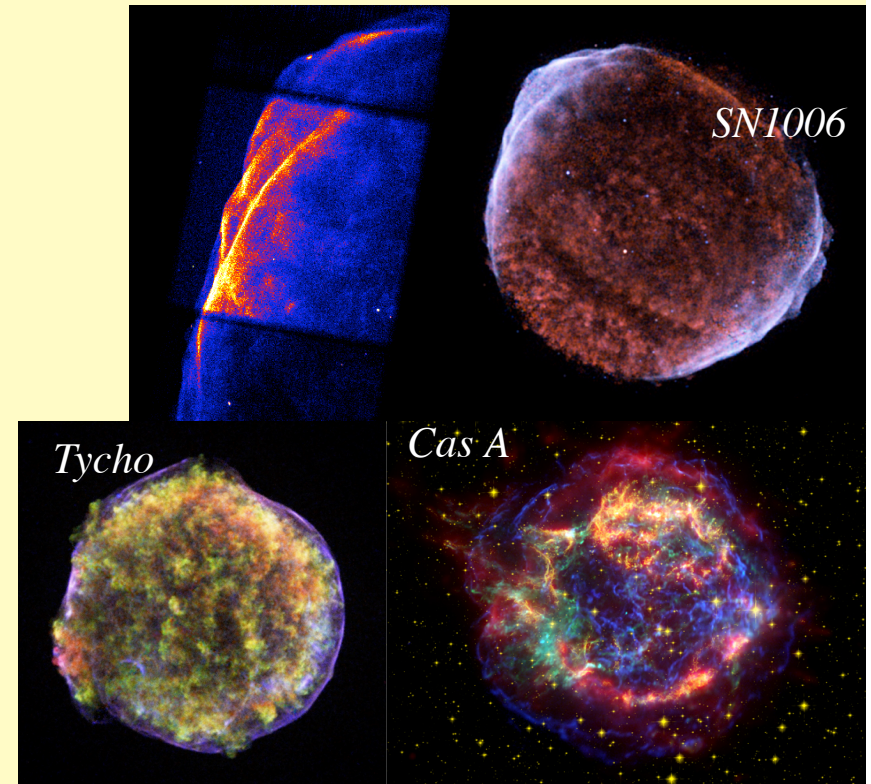


# Physics of Hot Gas

- Cooling
  - Two phase cooling
- Thermal conduction
  - Cold fronts
- Viscosity?
- Reynolds' Number
- Cosmic rays, Magnetic field (shocks)

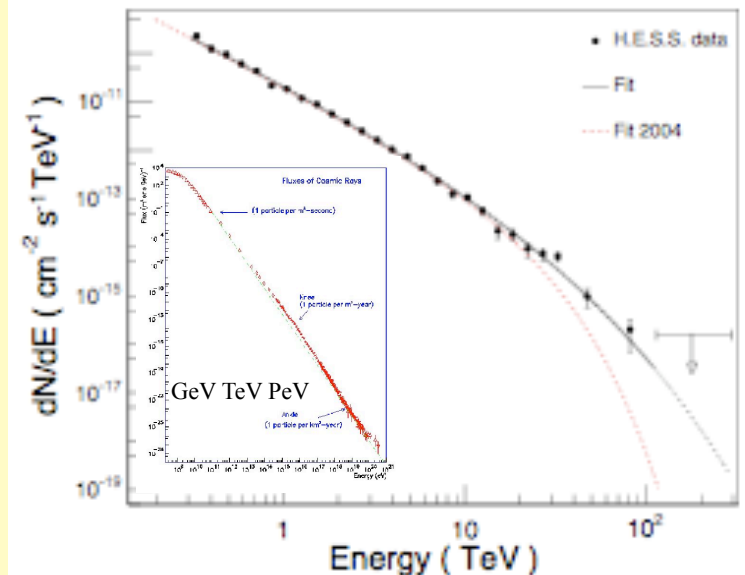
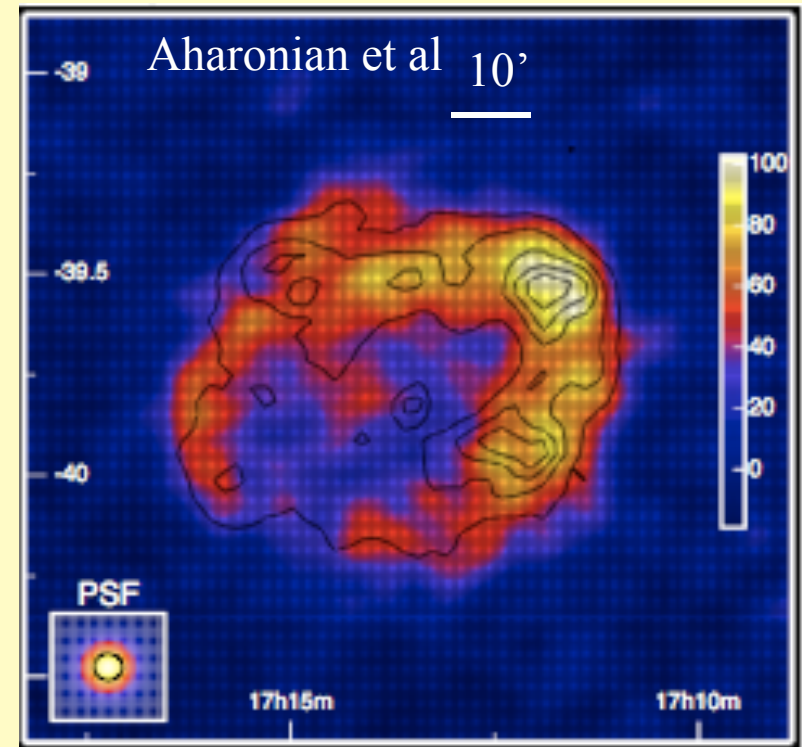
# Nonthermal electron acceleration

- Diffusive Shock Acceleration
  - Transmit CR protons with  $P_{CR} \sim E^2 N(E) \sim E^{-2} \sim 0.1 \mu u^2$
  - $P_e \sim 0.03 P_p$
  - Accounts for GCR after including propagation
  - Observed in IPM
  - Generic - eg clusters of galaxies
- Radio observations of SNR
  - Relativistic electron spectrum
  - Tycho, Cas A....
- X-ray observations of SNR
  - 2-100 keV
  - 100 TeV electrons
  - Variable (Uchyama et al)
  - $>0.1$  mG fields



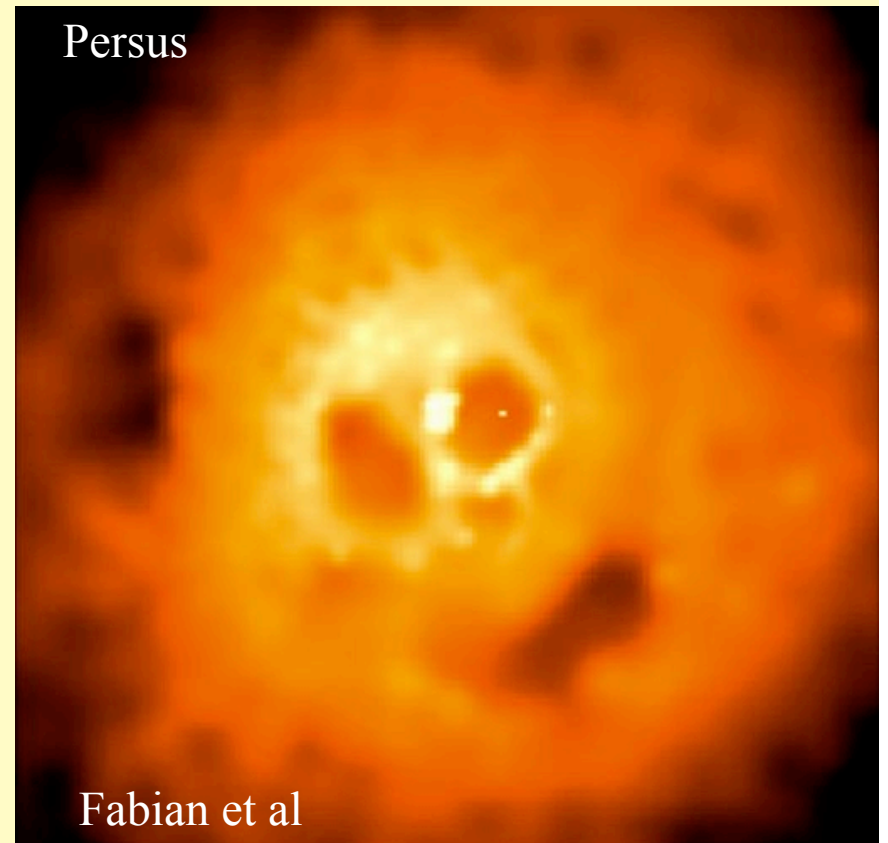
# Proton Acceleration?

- RX J1713.7-3946
  - AD385,  $R \sim 10\text{pc}$ ,  $u \sim 3000\text{ km s}^{-1}$
  - $\rho \sim 10^{-25}\text{ g cm}^{-3}$ ;  $P_- \sim 10^{-12}\text{ dyne cm}^{-2}$ ;
  - $P_+ \sim 10^{-8}\text{ dyne cm}^{-2}$ ;  $M \sim 150$
- $\sim 0.1\text{ PeV } \gamma\text{-rays}$ 
  - Inverse Compton by electrons?
  - Pion decay from protons?
  - Accelerate  $\sim 0.3\text{ PeV}$  protons?
  - Explain knee in GCR spectrum
- $L_x/L_\gamma \sim 3 \Rightarrow$  hadronic emission?
  - $\Rightarrow P_+(100\text{TeV}) \sim 10^{-10}\text{ dyne cm}^{-2}$
  - $\Rightarrow P_+(\text{GeV}) \sim 10^{-9}\text{ dyne cm}^{-2} \sim 0.1 P_+$
  - $P_+(e) \sim 3 \times 10^{-11}\text{ dyne cm}^{-2}$
- Particle transport
  - $r_L \sim 4 \times 10^{12} E_{\text{GeV}} B_{\mu\text{G}}^{-1} Z^{-1} \text{cm}$
  - $\langle u \rangle R/c$



# Relativistic particle acceleration by collisionless shocks is generic

- High Mach number shocks should transmit ( $> \text{GeV}$ ) protons
- Partial pressures  $\sim 0.1\text{-}0.3 \times$  thermal pressure
- Also electrons with lower partial pressure
- eg hot intergalactic medium
- No escape from universe
- Nearby clusters should be GLAST sources

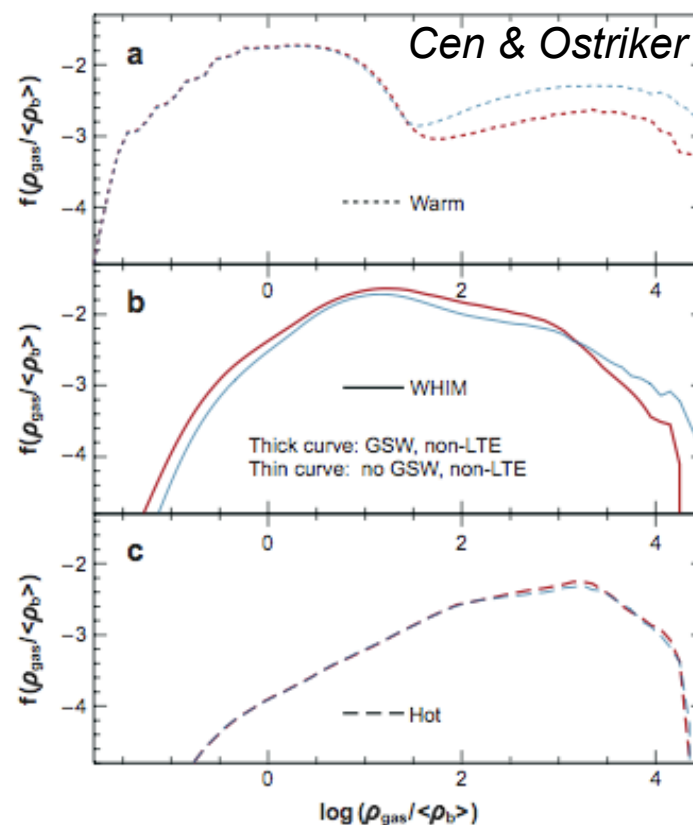


# Local WHIM

- IGM density at  $z \sim 3$  consistent with BBN
- “Missing baryons” (Persic & Salucci, Fukugita et al)
- Galaxies and Clusters:  $0.1 \times \Omega_b$ 
  - Hot gas galaxy halos
    - Ram pressure stripping?
- Cool ( $< 10^5 K$ ):  $0.3 \times \Omega_b$ 
  - Ly $\alpha$  – less than high  $z$
- Warm ( $1-5 \times 10^5 K$ ):  $0.5 \times \Omega_b$  ?
  - OVI abs, broad Ly $\alpha$
- Hot ( $0.5-2 \times 10^6 K$ ):  $0.1 \times \Omega_b$ 
  - OVII, OVIII abs
  - Only in galactic halos?

Definitions?

Model observation conflict?



# Cosmology

- X-ray record is good!
  - $\Omega_m, \sigma_8 \dots$
  - Relaxed clusters  $\rightarrow f_{\text{gas}}$
- Dark Matter
  - Bullet cluster et al DM non collisional
  - MOND/TeVS etc...
- Dark energy
  - X-rays largely ignored by DETF!
  - Can cluster observations provide a competitive measure of the evolution of dark energy?
    - ~500 relaxed clusters?
    - Do we know cluster properties well enough?
  - Are SZ clusters being found as expected?

# Future

- GLAST
- NuSTAR
- NeXT
- Wide field survey telescopes
- Simbol-X
- e-Rosita
- Constellation-XEUS

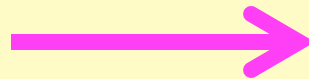
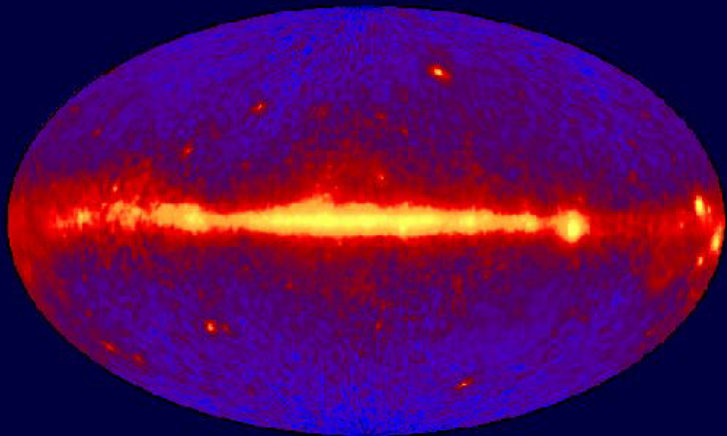


# GLAST

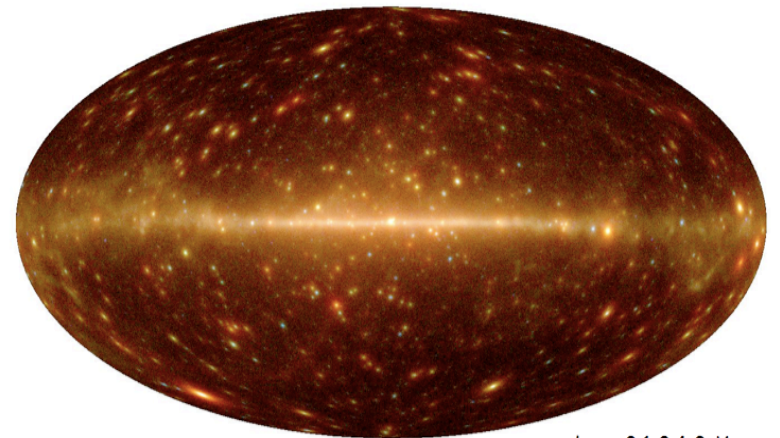
- Joint NASA-DOE-Italy- France-Japan-Sweden, Germany... mission
- Launch June 4 2008?
  - Cape Canaveral
- 50-100 x EGRET; high energy extension
  - Future program likely ground-based for a while
  - TeV astronomy



EGRET All-Sky Gamma-Ray Survey Above 100 MeV



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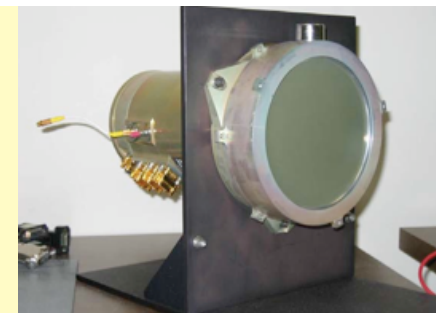
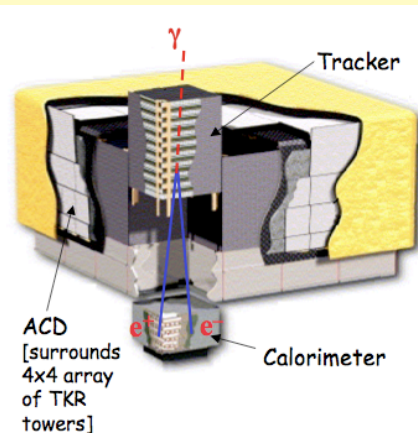
red: 0.1-0.4 GeV  
green: 0.4-1.6 GeV  
blue: >1.6 GeV



# GLAST

## LAT

- 0.02 - 300 GeV
- 2.5 sr, 0.3 - 0.9m<sup>2</sup>
- 5° - 5' resolution
- $\Delta \ln E \sim 0.1$
- $3 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  (>0.1 GeV, point source)
- $10^9$  photons (3Hz)
- All sky every 3hr



## GBM

- 0.01-30 MeV
- 9sr, 100 cm<sup>2</sup>.
- 1° resolution
- $\Delta \ln E \sim 0.1$
- Combine with Swift

## Sources after a decade?

- 10,000 Active Galactic Nuclei
- 1000 Gamma Ray Bursts
- 100 Pulsars
- 100 Supernova Remnants
- 10 Galaxies
- 10 Clusters of Galaxies
  - Cosmic rays, dark matter
- 10 X-Ray Binaries
- ? Unidentified Sources

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